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LUNAR PHYSICAL PARAMETERS STUDY

PARTIAL REPORT No. 5

MEASUREMENT OF LUNAR THERMAL PROPERTIES

A FEASIBILITY STUDY

TEXACO, INC.

December 7, 1960

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I. ABSTRACT

This report discusses in detail methods considered feasible to accomplish the following lunar thermal measurements.

1. Surface temperature.
2. Subsurface temperatures as a function of depth below surface.
3. Thermal diffusivity by measurements made at surface.
4. Thermal diffusivity by measurements made subsurface.

Instruments must be devised to carry out the measurements, and a testing and development program is required to establish the attainable accuracies in measurement. The following steps are proposed in such a program.

1. Suitable total radiation detectors with measuring circuitry must be built and evaluated.
2. There must be established the means of data treatment required to calculate thermal diffusivities from the different systems proposed.
3. A literature survey and/or experimental program should be undertaken to establish;
 - a. emittances and reflectances (spectral) of mineral systems considered reasonably similar to those of the moon, and
 - b. gross values of these properties by high resolution astronomical observation.
4. An experimental program is needed to evaluate the arrangement of measuring thermal diffusivity.

II. INTRODUCTION

Since submitting the last report¹ on thermal measurements, visits were made to the National Bureau of Standards and the Naval Research Laboratory, both at Washington, D. C., and to Jet Propulsion Laboratory, Pasadena, California. At the National Bureau of Standards and the Naval Research Laboratory, the problems of thermal measurements on the moon were discussed with staffmembers experienced in the techniques proposed. There seemed to be a general agreement that the methods of measurement proposed in the first partial report offered the highest probability of success. While at Jet Propulsion Laboratories there were opportunities to discuss the measurements and data interpretation with specialists in various fields, allowing clearer definition of the difficulties to be expected. This present report is based in part on the references, suggestions, and comments offered by these consultants. It has been considered unnecessary and, in fact, impossible in the time given, to perform instrument development work as a part of the feasibility study. In general, the techniques proposed use instruments and methods commonly in use, requiring refinement for the unusual conditions to be experienced. In addition to knowledge of instrument behavior, data interpretation will require good estimate of certain environment properties which may have to be the subject of an experimental program since brief literature search indicates a scarcity of data.

III. ELECTROLYTIC MODEL STUDIES

During earlier parts of this study, consideration was given to a system of temperature gradient determination using a thermocouple measurement of the temperature of a drill bit at various depths

¹Partial Report No. 2, Measurement of Lunar Thermal Properties, Texaco Inc., Aug. 31, 1960

below surface. Since the thermal conductivity of metals is on the order of a thousand times greater than the upper limit given for the conductivity of the lunar material, it was presumed that temperature measurement within the drill bit would average the temperature over the depth penetrated, and in addition would require long time periods to come into thermal equilibrium with the bore hole. The problem of attaining thermal equilibrium has been estimated in the previous report (see Fig. II - Lunar Physical Parameters Study - Partial Report No. 2 - Measurement of Lunar Thermal Properties).

To estimate the averaging effect on temperature of a drill stem inserted into a bore hole, an electrolytic model was constructed. The use of such models is discussed by Jakob, Volume 1, Chapter 20 (Jakob, Max - Heat Transfer, Vols. I & II, John Wiley & Sons, Inc., New York, 1957). The basis for such use is the fact that the differential equation describing heat flow holds true also for electrical flow, allowing the use of electrical analogs to model heat flow systems. The particular model used to evaluate gradient measuring systems is sketched in Fig. 1. Within the electrolyte, electrical potential gradients are set up by the current flow between the copper plates. These gradients are detected by a probe inserted through the bushing. A point-to-point measurement of electrical potential is made by insulating the probe except for a small exposed area at the tip. To simulate the effect of a rod of metal inserted into a material of low thermal conductivity, the probe for electrical potential determination can be bared over its entire surface. Figs. 2 and 3 give the results of this model work. The electrolyte used within the model had an electrical resistivity of 500 ohm cm and the

probe used was copper with a resistivity of 1.7×10^{-6} ohm cm. The model, therefore, represents the effect of introducing a probe which forces an isopotential (isothermal) boundary over areas exposed to the electrolyte (material of low thermal conductivity). Fig. 2 gives results for a uniform gradient within the electrolyte, Fig. 3 is for a system where the gradient was changed within the electrolyte by the presence of a styrofoam grid which reduced the volume of conducting electrolyte in a well-defined region.

The conclusions from this work are that measuring temperature profiles within a material of low thermal conductivity by use of a metal probe acting as an isothermal boundary averages temperature along the depth penetrated and that because of this averaging changes in thermal gradient may be ill defined.

IV. INSTRUMENTATION

1. Surface Temperatures

The first partial report dealing with thermal measurements estimated uncertainties associated with the use of total radiation detectors and of thermocouple and thermistor devices to measure temperatures of the lunar surface. The thermocouple and thermistor devices require an accurate and reliable placement at the surface to be studied, and give an error in temperature reading due to heat flow along connecting wires. This temperature error due to heat leak becomes considerable when the surface contacted has a low value of thermal conductivity (see Lunar Physical Parameters Study - Partial Report No. 2 - Measurement of Lunar Thermal Properties for quantitative estimates). The errors associated with use of thermocouple and thermistor devices seem extremely difficult to

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estimate from earth for proper data interpretation. Therefore, it was decided that thermistor and thermocouple devices would be a poor choice for reliable temperature data. The use of a total radiation detector eliminates the problem of mechanically coupling to the surface and offers the least possible disturbance of surface temperature. For accurate determination of temperature from measurements of emission of radiant energy, surface properties of emittance and reflectance must be estimated, but it seems more reasonable to estimate these quantities than to estimate the coupling errors inherent in use of thermocouples and thermistors. Some of the terminology used in discussing radiation detectors is defined in Appendix B.

The total radiation detectors can be made as small units, estimated to be a cube less than two inches on a side weighing less than one half pound. For surface temperature measurement, the following combinations can be used, given in order of complexity:

(1) Single Radiation Detector

A single unit precalibrated on earth fixed in place on the instrument package with no provision for calibration check or scanning. If the sensor is a thermocouple device, output is in millivolts. If the sensor is a bolometer or thermistor style of device, a resistance change in the element must be translated into a signal. No matter what sensor element is used, the temperature of the sensor environment must be accurately known for determination of the temperature of the viewed surface. This means two outputs per unit.

A unit of this kind has the obvious disadvantage of

seeing only one very small, specific area of surface for temperature determination. To allow more sampling, either of two systems may be used.

(2) Multiple Radiation Detectors

Several units as described in (1) set to view different areas of surface. Failure of one of the units does not mean complete loss of surface temperature data.

(3) Single, Scanning Radiation Detector

A unit as described in (1) set to traverse surrounding areas of surface in some preset configuration. Calibration can be built into this unit by allowing it, at some part of the cycle, to view either a surface of known characteristics and temperature or to view an empty portion of space.

On any of the combinations of (1), (2) or (3), data interpretation would be aided considerably if, by use of television, the physical appearance and gross geometry of the surfaces viewed were known.

An increased confidence in data can be obtained by adding the additional complexity of a calibrating device to the radiometers. At intervals a mirror can be placed in front of the detector to allow it to look at either a surface of known characteristics and temperature, or at an enclosure acting as a blackbody. Use of the calibrating device would require power to attain the desired calibrating temperature and a thermocouple output to know this calibrating temperature accurately.

In considering the outputs of these sensors, wherever a thermocouple measurement is mentioned, the millivolt difference must be used with some absolute device to determine reference

junction temperature. If all thermocouple leads are brought back to a common reference point of temperature, a single resistance thermometer or thermistor can be used to read the reference temperature. Where temperature measurements are desired at several points, use of thermocouples leading to a common reference point of temperature seems the least cumbersome system to use.

In Fig. 5 is plotted the emission of a blackbody according to the Stefan-Boltzmann Law. A very rapid drop in emitted energy is noted with reduction in temperature. The radiation detector will be operating presumably in the range of 300°K and the sensing element changes temperature as a result of the radiant energy interchange with the surface viewed. A temperature change of the surface at 100°K affects the net radiation interchange with the sensing element to a much lesser extent than an equal temperature change of the surface at higher temperatures. The Stefan-Boltzmann equation for a blackbody is,

$$E = \sigma T^4 \quad (\text{see Appendix A}).$$

Thus, for the change in emitted energy of a blackbody as a function of temperature,

$$\frac{dE}{dT} = 4 \sigma T^3$$

$$\text{at } 100^\circ\text{K} \quad \frac{dE}{dT} = 4 \sigma (10^6)$$

$$\text{at } 200^\circ\text{K} \quad \frac{dE}{dT} = 4 \sigma (8 \times 10^6)$$

$$\text{at } 300^\circ\text{K} \quad \frac{dE}{dT} = 4 \sigma (27 \times 10^6)$$

Unless some provision is made for changing instrument sensitivity with temperature of the surface, a much reduced accuracy of temperature measurement will be experienced at the lower temperature of surface.

2. Surface Determinations of Thermal Diffusivity

A simple reflecting shield placed over the surface during the lunar day gives a shadow which should produce in miniature the temperature variation observed during eclipse. A blackbody temperature sensor at the center of this shield facing the surface then follows the temperature at the center of the shaded area as a function of time. Knowing the solar energy entering the surface outside the shaded area, having an estimate of the original temperature distribution within the lunar surface layer, and knowing the geometry of the system (which would include a knowledge of angle of incidence of solar radiation) should allow solution of the heat flow equations and determination of a thermal diffusivity for the surface layer. This would be a rather complex mathematical treatment, quite possibly best solved by some form of analog computer. Consideration of space and weight limitations, the sensitivity of available temperature sensors, and the estimated properties of the surface will give an optimum size of the reflector shield. Temperature data available for the moon indicate a surface gradient on the order of $2^{\circ}\text{C}/\text{cm}$ (see references 1 and 4, Lunar Physical Parameters Study, Partial Report No. 2, Lunar Thermal Properties). The electrolytic model was used to estimate the relationship of radius of shield to depth below surface for lines of equal temperature. The attached Fig. 4 summarizes results of this work. A shield of radius r gives a temperature at the center of the shaded region equal to the temperature at a depth $\frac{r}{1.3} = 0.77r$. Thus, if a temperature gradient of $1^{\circ}\text{C}/\text{cm}$ is estimated, a shield 20 cm in diameter gives a temperature at center differing from the unshaded surface by an

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amount $.77 \times 10 \times 1 = 7.7^\circ\text{C}$. Use of the model thus indicates measurable differences in temperature can be obtained with reasonable dimensions of the shield. These figures are useful only as a rough guide since the electrolytic model as used contained a uniform conducting medium, and presumably stratification exists in the surface layers of the moon. In addition, if a local condition of high thermal conductivity exists the large values of temperature gradient will not be found. An upper limit of thermal diffusivity will exist for each shield dimension above which the temperature difference between the shadow center and the exposed surface becomes small enough to give large inaccuracies in diffusivity determination.

A second method of estimating thermal diffusivity is possible by addition of simple measuring circuits to the instrument package itself. If a temperature difference exists between the lunar surface material and an instrument package, a heat flow along the package support will result (this presumes the package is held off the surface by legs of some sort). The disturbance in surface temperature at the area of contact of the legs will be a function of the thermal diffusivity of the lunar material. Thus, by measuring the thermal gradients along the leg and knowing its dimensions and materials of construction, the quantity of heat transferred can be determined. Further, the interface temperature and area of contact can be known. If a true surface temperature is known by radiation detector the thermal diffusivity can be computed as in the case of the reflecting shield. Thus, by adding sufficient instrumentation to determine the temperature gradient along a supporting leg and also the temperature of the end in contact with the lunar material,

an independent estimate of the thermal diffusivity can be made. Probably the easiest means of estimating thermal diffusivity with equipment of this type would involve a prior empirical calibration. It would be desirable in any case to estimate the area and nature of surface contact by an independent means, e.g., a television view.

Another method of measuring the diffusivity would be by using an external light source and a total radiation pyrometer. This measurement would be made at night after the lunar surface temperature has essentially reached equilibrium, i.e., a small change in temperature over one hour. A radiation pyrometer would be needed which would have a relatively short response time. Pyrometers are commercially available having response times as low as 10 milliseconds although most units have a lower limit at 0.6 seconds.

There should be an instantaneous apparent temperature rise due to reflected radiation. If the incident flux were known, a gross reflectivity of the radiation for the specific light source would be measured. It may be necessary to mismatch, by suitable filtering, the light source and the pyrometer so that the reflected radiation is not too intense.

Shortly after the light source is turned on, the temperature of the surface will increase. The rate of increase will be determined primarily by the diffusivity of the material. The lower the diffusivity, the more rapid the rise in temperature to its final temperature. Similar problems have been treated by Carslaw and Jaeger, first edition, Page 51 and by A. F. Wesselink (Bull. Astron. Soc. of Netherlands, X (1948), 51) who determined the conductivity from eclipse data.

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A rather simple laboratory experiment was carried out in air to determine the order of magnitudes of the time constants (i.e., the time to reach $1 - \frac{1}{e}$ of its final value) involved. A thermocouple was placed inside a $1/8$ " diameter hole drilled parallel and $1/8$ " below the surface of a firebrick having an approximate diffusivity of $5 \times 10^{-3} \text{ cm}^2/\text{sec}$. The brick was heated with a 150 watt infrared lamp placed 6" from the brick. It took 200 seconds for the temperature to reach $1 - \frac{1}{e}$ of its final value. It is realized that this is a very crude experiment, but it shows, even in the presence of air, that the time involved to raise the temperature of a relatively poor conductor is on the order of a few minutes. This time is proportional to the diffusivity. Therefore, for diffusivities on the order of $10^{-5} \text{ cm}^2/\text{sec}$., it would be expected that the temperature will reach its maximum value in a time greater than one second.

The above estimate is for a localized area. Pettit's data on the eclipse taken over a relatively broad area, showed that the minimum temperature was realized in a period below 1 hour. Therefore, it would seem reasonable that the times involved to reach $1 - \frac{1}{e}$ of the final value of temperature for a localized area on the lunar surface would be greater than one second and less than one hour. It is feasible to work with times in this range.

The conclusion of the above discussion is that it would appear feasible to measure the diffusivity and a gross reflectivity for the lunar surface material using an external light source and a total radiation pyrometer. The light source could be of such intensity that the temperature rise of the moon's surface would not exceed that

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thought to be present during daylight. The emissivities calculated from the reflectivity data, would be useful in calculating the absolute temperature of the lunar surface. It would appear that this method should be investigated experimentally.

None of the feasibility study carried on thus far allows estimate of the accuracy in thermal diffusivity measurement inherent in the methods proposed. The data available will be temperature change and heat energy transferred. During design of the instruments, the errors expected in these measurements will become known. It is then necessary to solve the heat flow equations for the particular geometries and boundary conditions to determine the accuracy in estimation of thermal diffusivity. This will be a time consuming theoretical study necessarily carried on during instrument design.

3. Surface Determination of Spectral Data

It has been suggested that, since the intensity of incident solar radiation as a function of wave length at the moon's surface is known, a grating spectrometer be incorporated into the instrument package. A detector sufficiently sensitive to respond to the radiation intensity of a narrow range of wave lengths is needed, with an accurate alignment of grating, mirrors, and slits. Such an instrument would be useful in characterizing the surface, and specifically useful in temperature estimation since lunar surface emittance might be calculated with a certainty not otherwise possible. However, because of the necessity of maintaining at least one and, considering the wave length coverage, possibly two highly sensitive radiation detectors, the need for keeping an accurate and known alignment with provision for scanning the wave length range, and since the device

would not be generally useful as a temperature indicator, it will not be discussed in any greater detail. The usefulness of such spectral determination may well dictate inclusion of such a device as a separate experiment.

4. Subsurface Temperature and Diffusivity Measurements

Two systems of subsurface instrumentation have been considered in the overall study of the measurement of lunar physical parameters. The first considered was an instrument package integral with the drill bit for measurement as drilling progressed. For temperature determination by this system, the drill bit must be thermally decoupled from the main space craft and allowed to come to equilibrium with the surrounding formation after dissipating the waste heat from drilling. This decoupling can be accomplished by heat exchange systems near the lunar surface. A simple thermocouple or thermistor measurement of the drill stem temperature would give the average equilibrium temperature of the formation over the depth drilled. The type of averaging expected was discussed under the heading of electrolytic model studies. While simple in concept, the thermal decoupling requires complex equipment and sensitive instrumentation, and the arrival at equilibrium requires a prolonged time of measurement (see Lunar Physical Parameters Study - Partial Report No. 2 - Measurement of Lunar Thermal Properties).

Determining thermal diffusivity in this system would be done after drilling to depth, at which time the necessary heating element and temperature sensor would be left behind in the tip of the drill bit while the main body of the drill was removed. After attainment of thermal equilibrium, diffusivity would be determined at

hole bottom by following the temperature rise of the remaining package as a function of time with a constant rate of heat input. The previous Partial Report on Lunar Thermal Measurements discussed the advantages of supporting the diffusivity apparatus a slight distance from the formation to allow only radiation transfer as a heat exchange mechanism.

The second system of subsurface instrumentation involves construction of a logging tool to be used after completion of drilling.

Downhole temperature will be determined by measuring the equilibrium temperature and rate of heat dissipation of a blackbody radiator suspended beneath the downhole logging tool. Radiation shields, both above and below the radiator, will restrict the length of borehole "seen" by the radiator. In this way, it is hoped to minimize the temperature averaging which takes place in a blackbody cavity due to radiation interchange between the various parts of the cavity.

Heat dissipation in the blackbody radiator will be determined by measuring the thermal gradient in the support for the radiator. Obviously, final temperature determinations will be based on empirical calibration of the instrument.

This diffusivity can be measured by monitoring the temperature rise in the blackbody radiator when power is dissipated in the radiator at a constant rate. Preliminary calculations indicate that dissipation on the order of 1 watt for a period of 100 minutes should be adequate to yield order of magnitude values for the diffusivity in the range 10^{-6} to $10^{-3} \frac{\text{cm}^2}{\text{sec}}$. Calculations indicate that for

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radiation from a spherical iron ball of 1 cm. radius to an infinite medium whose initial temperature is 200°K bounded internally by a spherical cavity 2 cm. in radius at a rate of 6 cal/minute, slightly less than 12 cal/minute of total power need be supplied to the iron ball over the 100 minute period. As yet, temperature of the radiator as a function of time for constant rate of power input has not been computed, but it can be done using the solution for constant rate of power radiation. These results should be a first order approximation to the empirical calibration curves that will have to be obtained from such instrumentation.

The physics of the above downhole unit are quite similar to one of the systems proposed for measuring the diffusivity of the material on the lunar surface, namely, the method using an artificial light source. Therefore, basic studies of emissivities and solutions of heat flow equations would be applicable to both situations.

For accurate calibrations of temperature, diffusivity, and length of hole over which the measurements are averaged, the borehole diameter needs to be known. There will be some compensating effects present when the temperature and diffusivity are measured under conditions of a variable diameter borehole, but none for the length of the hole which the device "sees".

V. STUDIES NECESSARY FOR DATA INTERPRETATION

In a previous section of this report dealing with measurement of temperature, the use of total radiation detectors was discussed. The point was made that for accurate determination of

temperature from measurements of emission of radiant energy, surface properties of emittance and reflectance must be estimated. The establishment of reasonable values for these properties should form the subject of a study in the time period before lunar data becomes available. Necessary data does not seem to be readily available in the literature, thus requiring experimental work on mineral systems expected to be reasonably similar to the lunar surface. At the expected lower limits of temperature of about 100°K the emitted radiation is at a wave length approaching 30 microns requiring emissivity work out in the far infrared. For the purpose of proper data interpretation it is necessary to know the emissivity of these mineral systems as a function of wave length and temperature. If, for all reasonable mineral systems, the emissivity is on the order of 0.9 or greater the emissivity correction can, in all probability, be ignored. It has been suggested that better estimates of these properties might be made by high resolution astronomical studies from the earth's surface. This study should be considered further along with high altitude observation from outside the earth's atmosphere. Previous statements concerning the use of radiation detectors should not be interpreted to mean that off-the-shelf items can be purchased and used. Undoubtedly, a period of instrument development will be required before packages are assembled. The estimation of thermal diffusivity requires either an empirical calibration of the instruments used or the solutions to some highly complex mathematical systems. In this case it would seem particularly desirable to build a prototype instrument and gain experience in its use under controlled laboratory conditions.

VI.

APPENDIX "A"

(From Introduction to Modern Physics by Richtmyer and Kennard, Fourth Edition, McGraw-Hill Book Company, Inc., 1947)

In considering emitted energy measurement as a means of estimating temperature, it is useful to examine the computed curves of emitted energy as a function of temperature and of the wavelength of the maximum of the spectral energy distribution, also as a function of temperature. The Stefan-Boltzmann Law states that the total emissive power of a blackbody is proportional to the fourth power of its absolute temperature. This relationship may be written as $E = \sigma T^4$ and is plotted in Fig. 5. Planck's formula gives the distribution of energy with wavelength and may be written:

$$X_{\lambda} = \frac{8 \pi c h}{\lambda^5} \frac{1}{e^{ch/\lambda kT} - 1}$$

For the total radiant energy in unit volume of an isothermal enclosure:

$$X = \int_0^{\infty} X_{\lambda} d\lambda = 8 \pi c h \int_0^{\infty} \frac{d\lambda}{\lambda^5} \frac{1}{e^{ch/\lambda kT} - 1}$$

The wavelength of maximum energy can be derived and is

$$\lambda_m T = 0.2891 \text{ cm. deg.}$$

This is plotted in Fig. 6.

$$\begin{aligned} \sigma &= \text{Stefan's constant} = 5.735 \times 10^{-5} \frac{\text{erg}}{\text{cm}^2 \text{ sec deg}^4} \\ h &= \text{Planck's constant} = 6.610 \times 10^{-27} \text{ erg sec} \\ k &= \text{Boltzmann's constant} = 1.381 \times 10^{-16} \text{ erg/deg} \\ c &= \text{velocity of light} = 2.9978 \times 10^{10} \text{ cm/sec} \end{aligned}$$

VII.

APPENDIX "B"

DEFINITIONS OF RADIANT ENERGY TERMS

(From "Temperature, Its Measurement and Control in Science and Industry", Vol. I, pg. 1164 - Reinhold Publishing Corporation, New York, 1941)

Emissivity - defined for a material as the ratio of a rate of emission of radiant energy by an opaque body with polished surface of the material as a consequence of its temperature only, to the corresponding rate for a blackbody at the same temperature.

Emittance - the ratio of a rate of emission of radiant energy by an opaque body regardless of surface characteristics as a consequence of its temperature only, to the corresponding rate for a blackbody at the same temperature.

Note that the emittance has the emissivity as its lowest limiting value.

Reflectivity - defined for an opaque, polished portion of material as the ratio of a rate of reflection of radiant energy from its surface to the corresponding rate of incidence of radiant energy upon it.

Absorptivity - defined for an opaque polished portion of material as the ratio of a rate of absorption of radiant energy by it to the corresponding rate of incidence of radiant energy upon it.

Reflectivity and reflectance, absorptivity and absorptance have the same relation as emissivity and emittance. The following relationship exists between emissivity, ϵ , absorptivity, a , and reflectivity, r .

$$(\epsilon = a = 1 - r)_T$$

The subscript T is taken as indicating that not only the ϵ , a , and r are for the temperature T, but that the incident radiations also are such as occur in a blackbody cavity at the temperature T. If the incident radiation has a spectral distribution other than blackbody

FIGURE 1
ELECTROLYTIC MODEL

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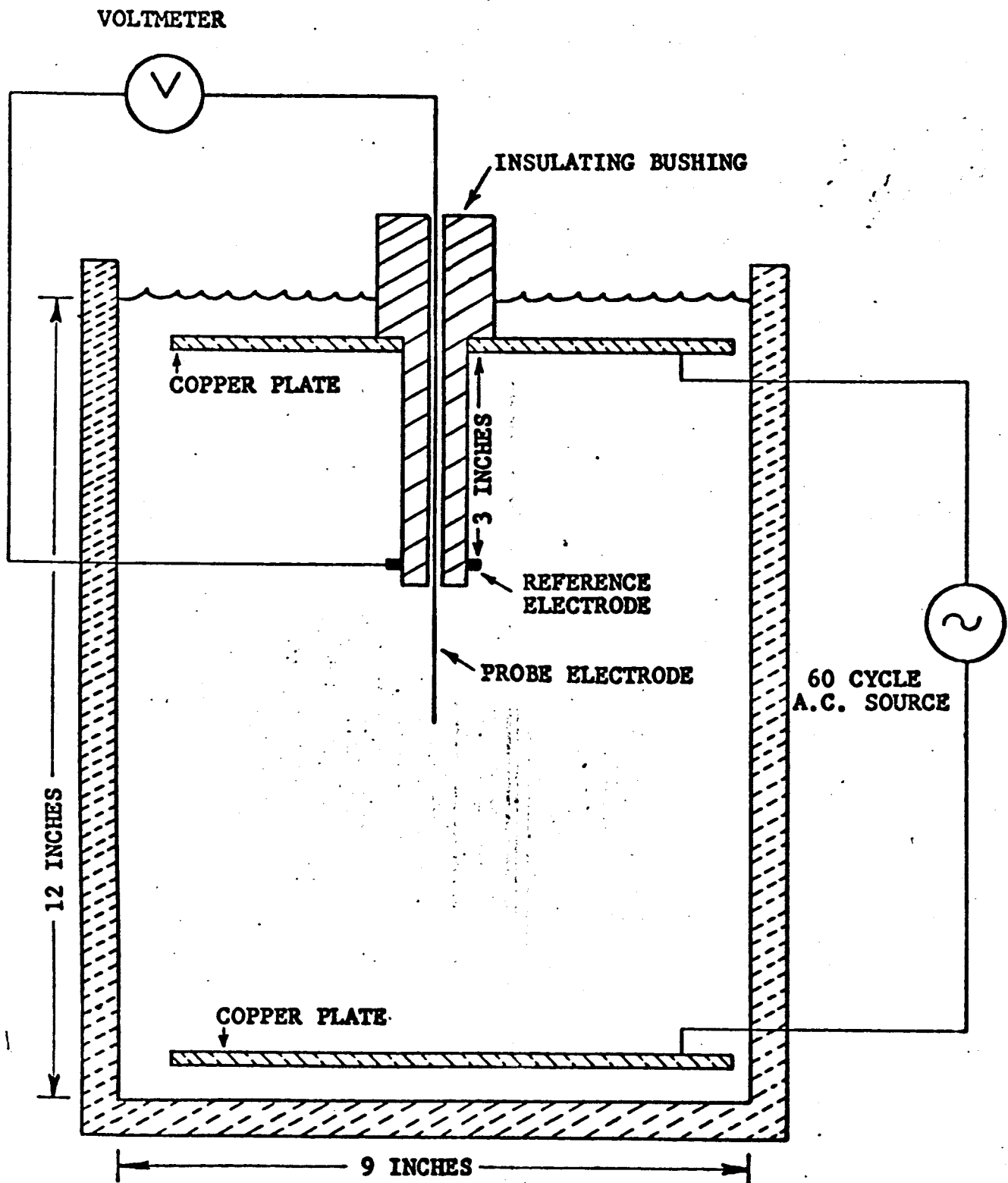


FIGURE 2
POTENTIAL GRADIENT CONSTANT WITH DEPTH

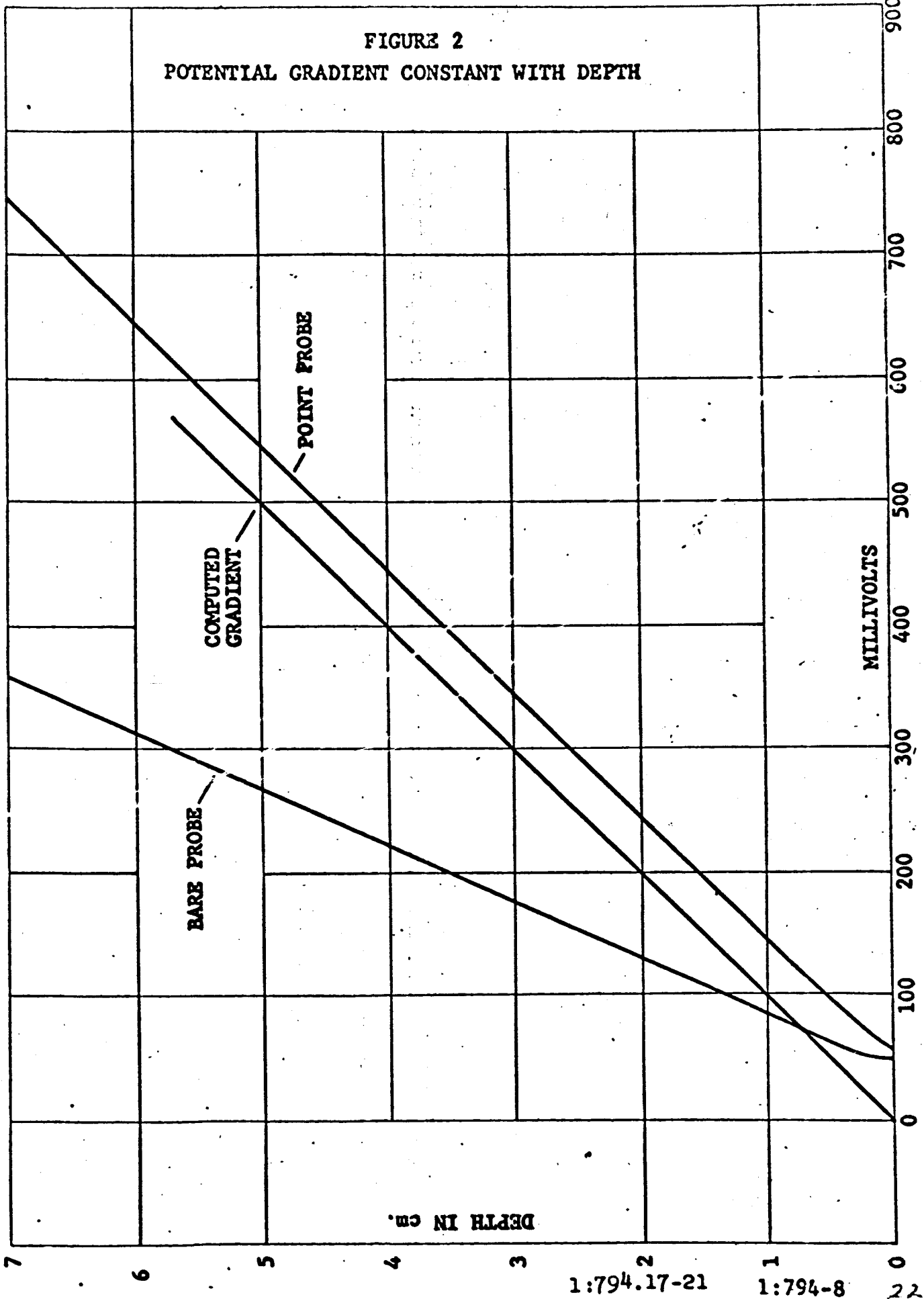


FIGURE 3
POTENTIAL GRADIENT CHANGING WITH DEPTH

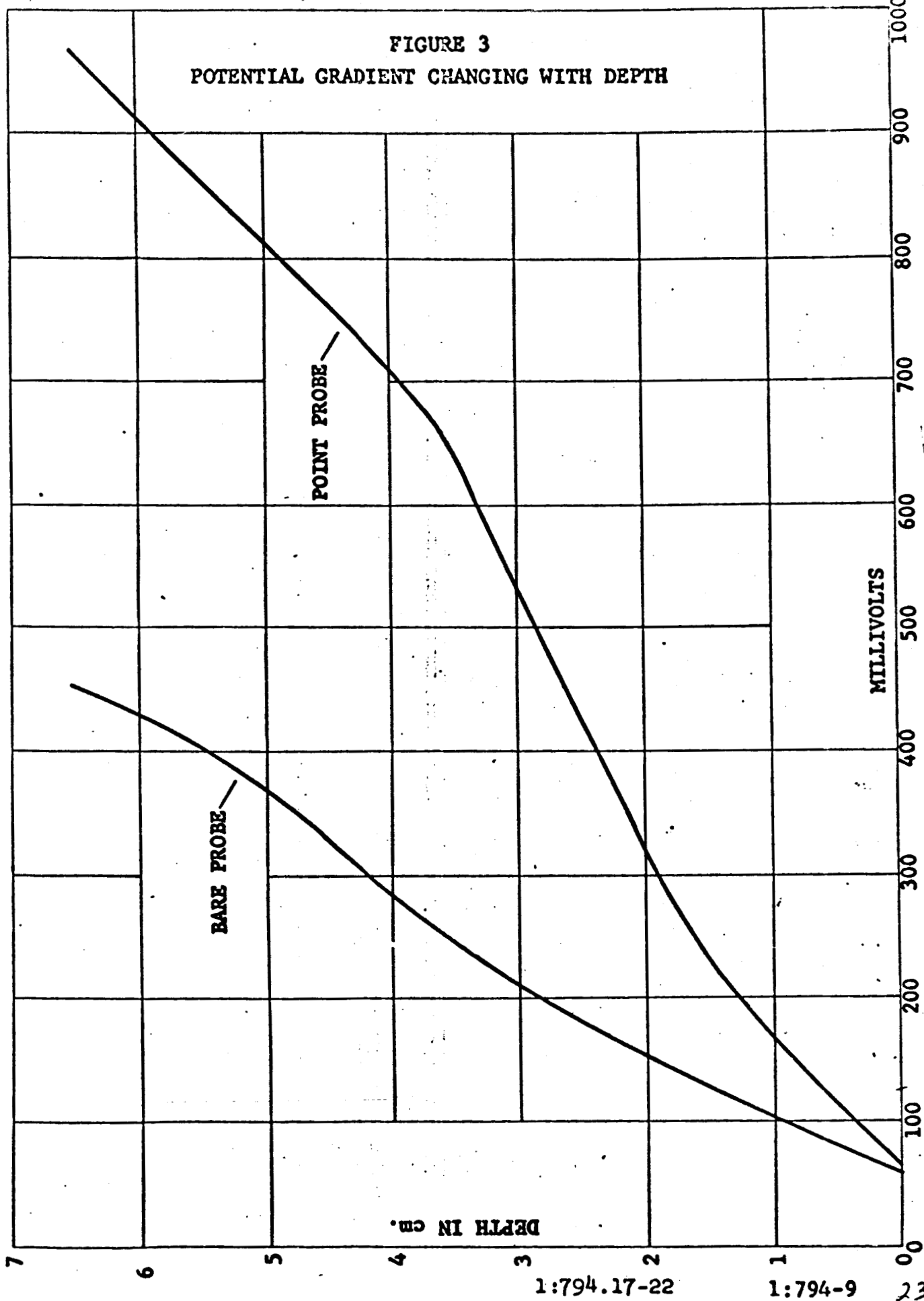


FIGURE 4

Plot of Radius of Shadow, r ,
 vs.
 Maximum Vertical Change In Isothermal, d ,
 and vs.
 Ratio, r/d

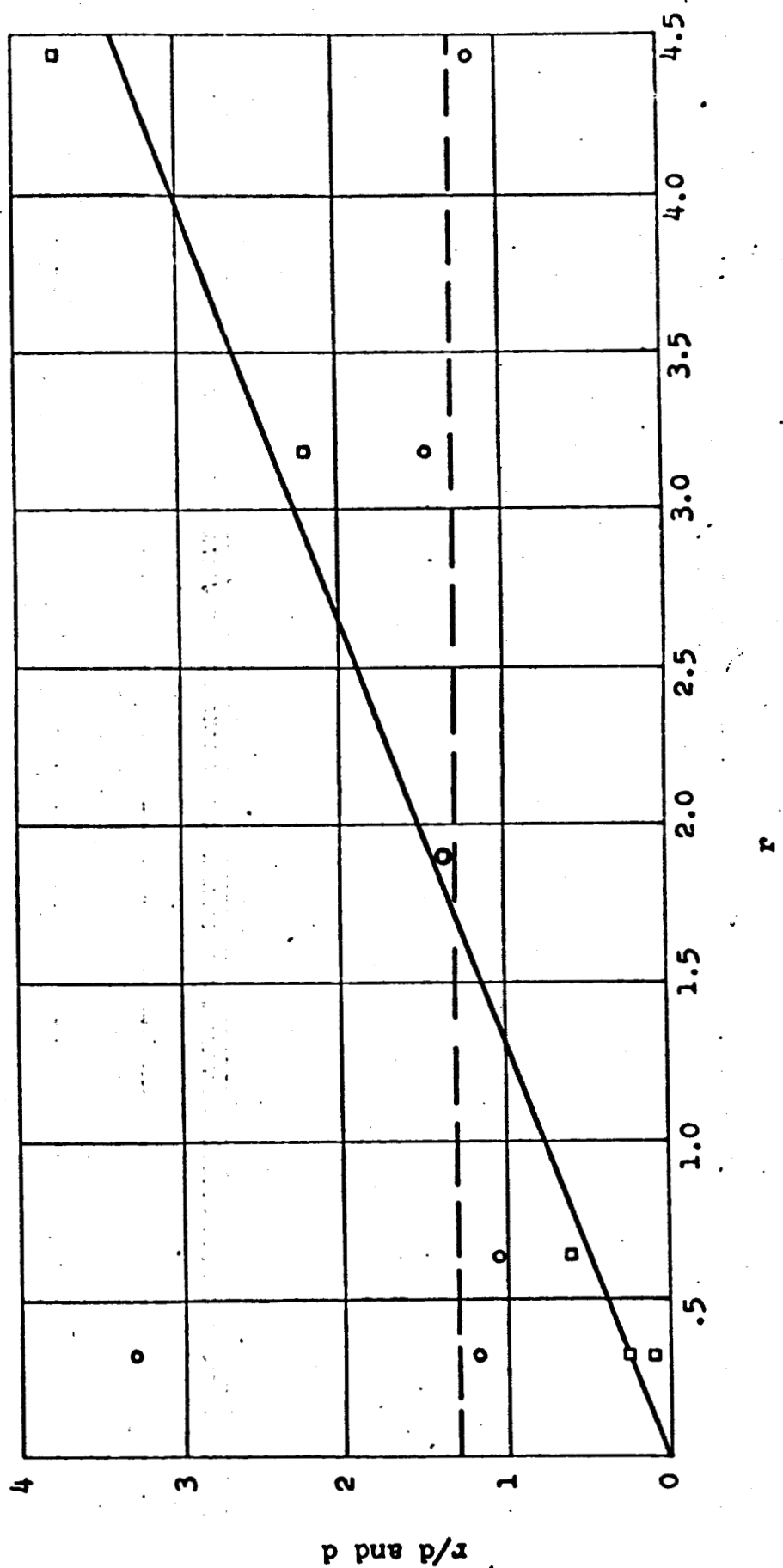
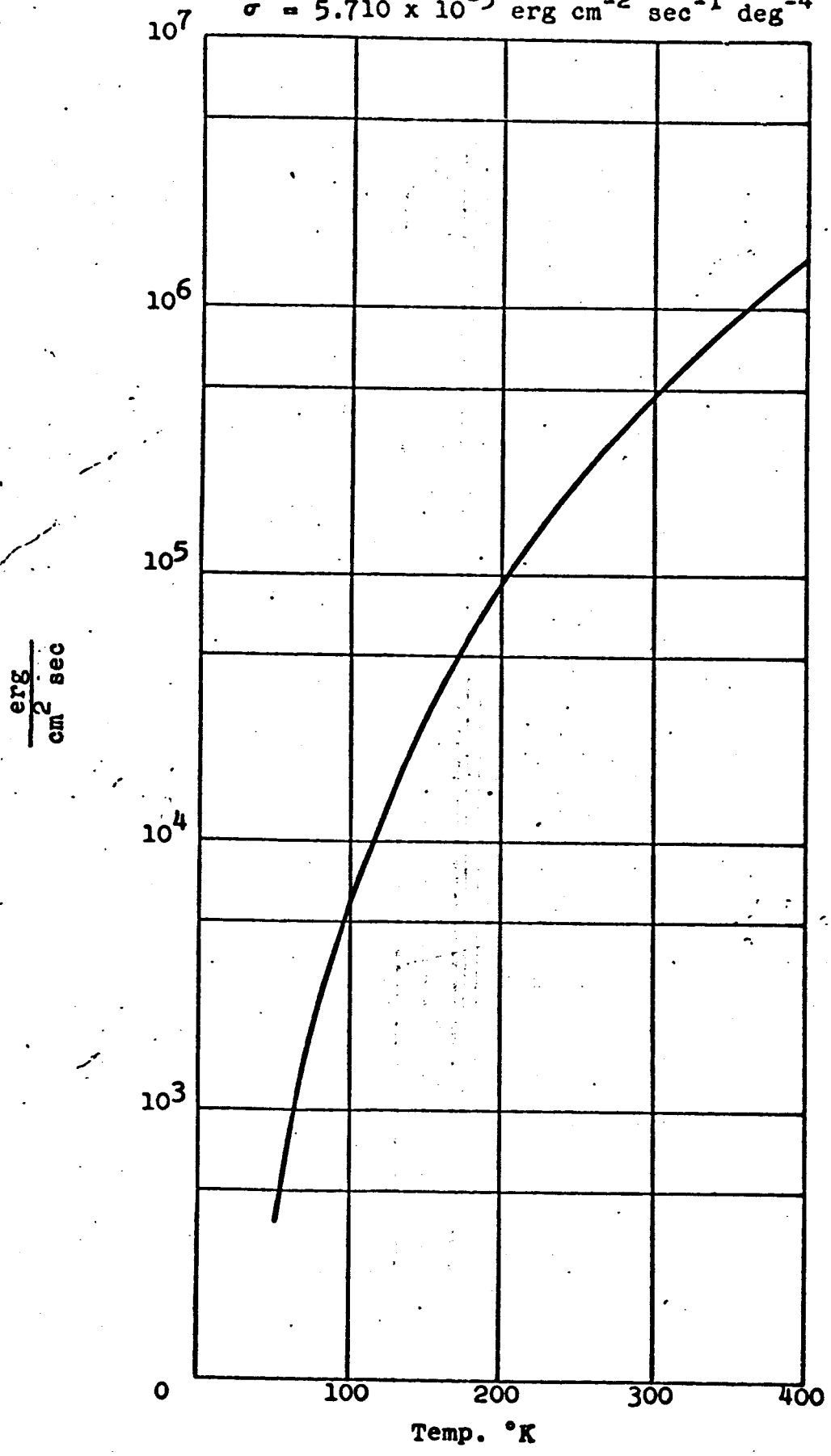


FIGURE 5

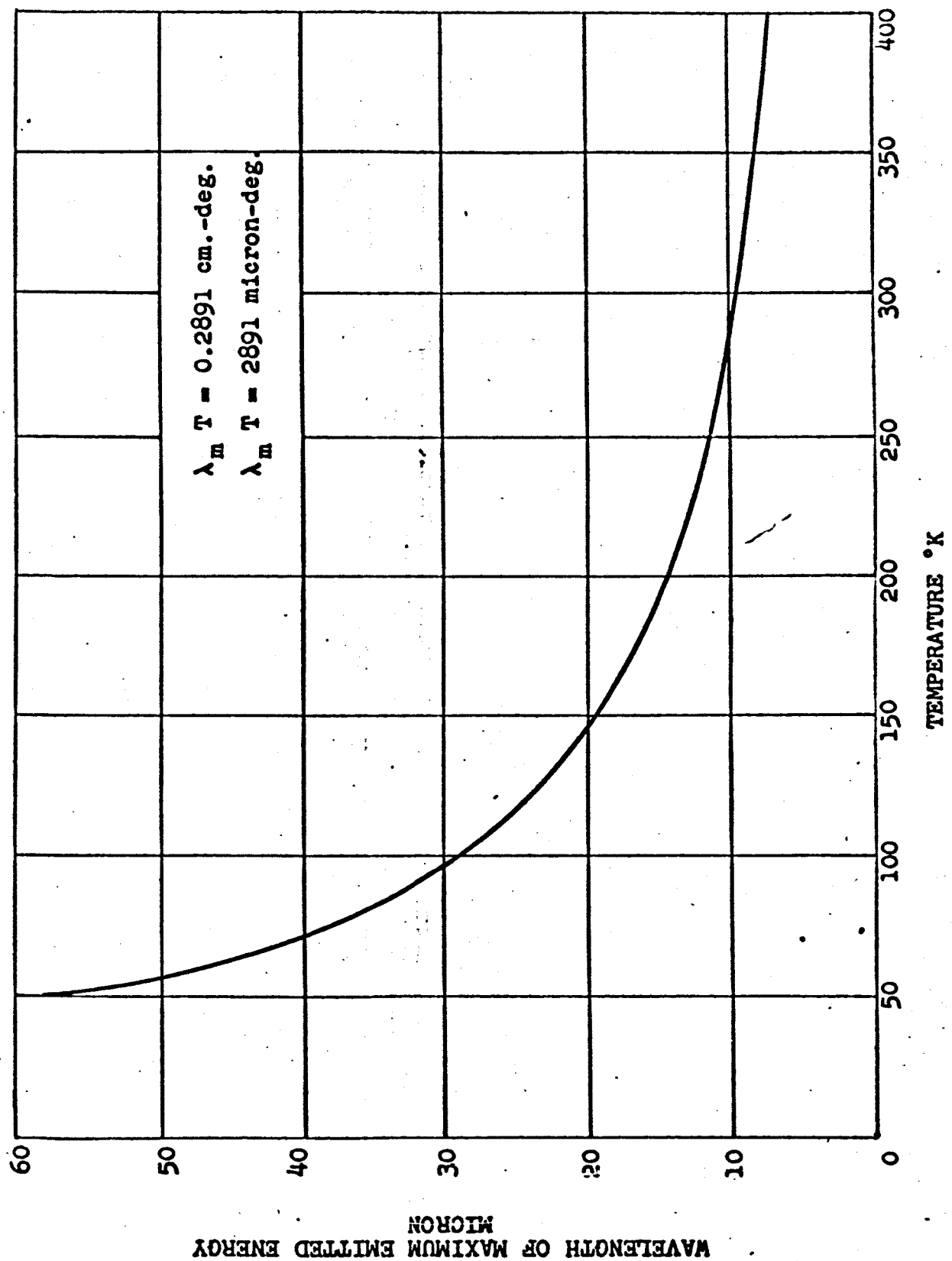
$$E = \sigma T^4$$

$$\sigma = 5.710 \times 10^{-5} \text{ erg cm}^{-2} \text{ sec}^{-1} \text{ deg}^{-4}$$



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1:794-16

FIGURE 6



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